AFAMRL-TR-83-047

THE EFFECTS OF Gx, Gy, *AND* Gz FORCES ON CONE MESOPIC VISION

DAVID A. TIPTON

OCTOBER 1983

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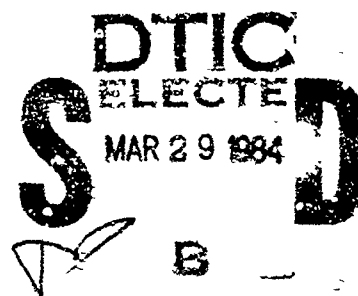
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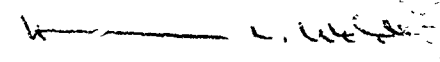## TECHNICAL REVIEW AND APPROVAL

AFAMRL-TR-83-047

The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Regulation 169-3.

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FOR THE COMMANDER

WILLIAM L. WELDE
Special Assistant
Biodynamics and Bioengineering Division
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The effects of Gx, Gy, and Gz acceleration forces on cone-type mesopic vision threshold values are examined. An experiment has been conducted on the Dynamic Environment Simulator, a three-axis human centrifuge, to reproduce an acceleration environment in a simulated night flight combat situation. Acceleration environments studied were levels of +1Gz, +1Gy, +1Gy, +1.4Gz, +2.0Gz, +3.0Gz, +2.0Gy in combination with +1Gz. A visual task was performed which determined 20/50 visual acuity illumination threshold values. The +gz environment is

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20. ABSTRACT (cont)

known to cause profound visual symptoms at relatively high levels. In this study, lower +Gz values were chosen to examine the more subtle effects which occur in low luminance situations. The visual effects of the Gy environment have not been previously explored. The +Gx environment is not felt to have visual effects at low levels. Physiological parameters recorded were PaO_2 by ear oximetry, heart rate, and visual acuity threshold values. There were eleven male subjects, all members of the United States Air Force. Their ages ranged from 25 to 39 years (mean ± SD, 28.9 ± 4.1), weights from 140 to 200 pounds (174.6 ± 8.2 lbs.), and heights from 66.5 to 74 inches (70.8 ± 2.6 ins.). Results were zero means obtained by self pairing with +1Gz controls. Analysis was done by two tailed t-test. Results showed no significant shift if luminance threshold values at +1Gy or +1.4Gz; significant increase in luminance threshold at the .05 level for +1Gx; and significant increase in luminance threshold at the .01 level for +2.0Gz, +3.0Gz, and +2.0Gy in combination with +1Gz. Results will be discussed with respect to individual variation, daily variation, wearing of glasses, cardiovascular effects, effects of head movement, and pulmonary effects.

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I would especially like to thank Adolph Marko, John Frazier, Dave Ratino, Lee Task, and Bill Slusher who spent a lot of time making sure my project would go smoothly.

I. OBJECTIVE

The objective of this investigation is to quantify changes from baseline of cone-type mesopic vision* threshold values in a simulated low cockpit illumination environment as a function of acceleration forces in a centrifuge.

II. INTRODUCTION

The advent of new offensive and defensive weapon systems is associated with challenging acceleration environments for the pilot. These new systems have accentuated the importance of night combat missions, with their associated aerial combat maneuvers, combined with the development of attitude independent acceleration along all aircraft axes.

The importance of the myriad aspects of night vision is rapidly becoming evident. Its many facets include night time target identification, [1-12] minimal cockpit illumination, [12-18] dark adaptation, [13,16,18-28] bright light recovery, [22,27,29,30] color cockpit lighting, [12-14,16-18,31,32] night vision enhancement systems [11,33-35] and night vision testing. [3,15,36-38] While these fields are being explored in the static environment, the documented effects in any axis of acceleration on night vision are virtually unknown. This paper will combine the aspect of mesopic vision threshold and linear sustained acceleration

*Whenever a glossary word first appears in the text, it will be underlined.

1

2

along the Gx, Gy, and Gz axes.

The literature on scotopic and mesopic vision has been concentrated mainly on static studies. There has been little work on the effects of acceleration on these important visual parameters. Some work was done by White, [39-42] but this involved only one subject and can therefore not be considered statistically representative of a target population. There has been virtually no other work done in this field.

The effects of Gz acceleration on various physiological parameters have been studied. [36,43-58] Photopic vision has been one of the most extensively studied in the aeromedical literature, both because of the importance of vision in the acceleration environment and because it is presently the single most reliable method of determining Gz tolerance. [48]

There has been some visual work in the Gx environment, [46,55,57] but to date, this work tends to indicate that man reaches his physiological endpoints before seriously affecting his photopic vision.

The Gy environment is a relatively new field of study. Previous technology was such that air crew members were unlikely to encounter such an environment, therefore, research in this area was felt to be nonproductive. However, with the advent of the Advanced Fighter Technology Integration F-16 (AFTI/F-16), sustained acceleration along the lateral axis is now possible. It becomes apparent that an examination of the affected physiological parameters is required.

III. BACKGROUND

VISION

The eye [21,23,59-67] is a lens system (See Figure 1); its primary purpose is to focus the incident light onto the retina. The retina con-
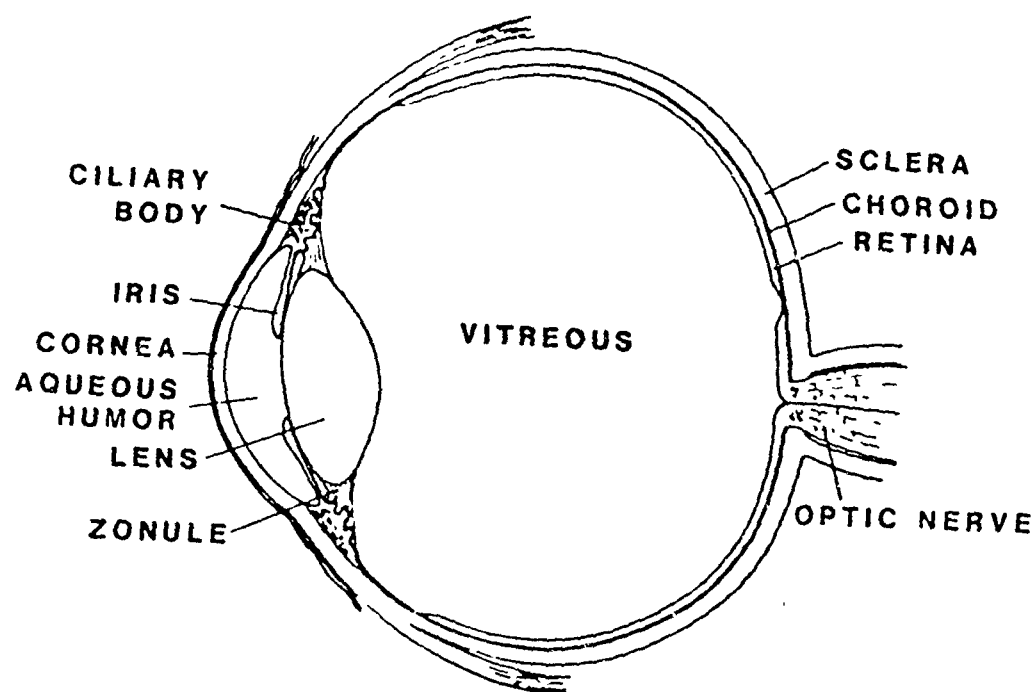
Figure 1. DIAGRAMMATIC SECTION THROUGH THE EYE
(FROM PHYSIOLOGY OF THE HUMAN EYE AND
VISUAL SYSTEM, HARPER & ROW,
PUBLISHERS)

tains receptor cells (rods and cones) which when stimulated by light

send signals to the brain. These signals are subsequently interpreted

as vision.

The eye is organized in such a way that the signals are partially

processed before they reach the brain. This is accomplished via auxil-

iary transmission cells (See Figure 2). The rods and cones synapse with

bipolar cells which subsequently synapse with ganglion cells. The axons

of the ganglion cells form the optic nerve, which carries the signals to

the brain. Also within this system are two other cells, horizontal

cells, which are responsible for horizontal processing between bipolar

cells, and amacrine cells, which are responsible for horizontal process-

ing between ganglion cells. This cross connection of cells is respon-

sible for certain low level processing and helps the visual system

interpret certain stimuli such as movement, low light level stimuli,

spurious nerve impulses and low contrast visual stimuli.

The rods and cones are high energy dependent cells with primarily

aerobic metabolism. As a result, they require a richly oxygenated blood

supply. In fact, the retina has the highest oxygen demand and the

lowest deprivation tolerance of any human structure.[66] In order for

the blood supply to meet the needs of these cells, and yet not be a

colored filter through which the unprocessed light must pass, it is

located behind the retina in the choroid.

The blood supply of the rods and cones is optimized by their place-

ment immediately in front of the choroid. They are, therefore, the most

posterior located cells in the retina. The unprocessed light stimulus

must pass through the inner most layers of the retina, consisting of the

bipolar, horizontal, ganglion and amacrine cells mentioned earlier,

SCHEMATIC STRUCTURE

PIGMENT
EPETHELIUM

PHOTORECEPTORS
(RODS & CONES)

HORIZONTAL CELLS

OUTER SYNAPTIC
LAYER

BIPOLAR CELLS

AMACRINE CELLS
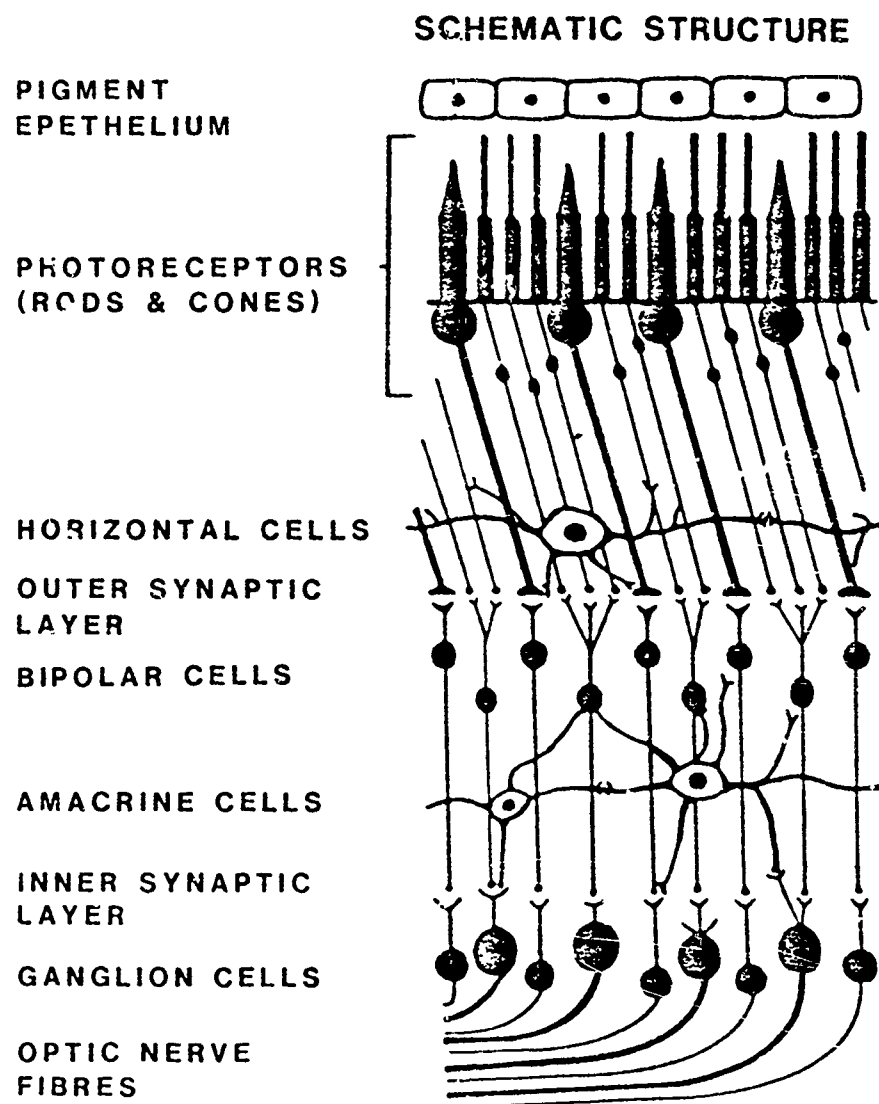
INNER SYNAPTIC
LAYER

GANGLION CELLS

OPTIC NERVE
FIBRES

Figure 2. A SCHEMATIC CROSS-SECTION
OF THE RETINA (FROM MEDICAL
OPTHALMOLOGY. C. V. MOSBY
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before it can be received by the rods and cones. The resultant scatter-

ing of light has a significant effect on visual acuity. As will be seen

later, the eye partially circumvents this problem.

The rods and cones are different in their anatomic, biochemical,

and physiological functions. [23,59,60,63,67] Their major similarity is

that they both contain a visual pigment which consists of a chemical

combination of vitamin A and an opsin. When a photon of the correct

wavelength strikes this visual pigment, it breaks down into its two

components. This chemical reaction releases a quantum amount of energy.

If enough quanta of energy are released, i.e., if enough photons stimu-

late enough molecules of visual pigment, the nerve cell is stimulated,

and a "light" signal is sent to the brain for interpretation. After

this reaction occurs the vitamin A and the opsin are recombined, via an

energy dependent process, into the original visual pigment. At this

point, however, the systems diverge.

In the rods, the visual pigment is rhodopsin. The rhodopsin is

sensitive to photons of wavelength between 400 and 640 nm. They are

insensitive to any red light of greater than 640 nm. The cones have

three different visual pigments, called chromopsins. These pigments are

sensitive to light spectra with peaks in either the red, green, or blue

region. When photons of the appropriate wavelength strike the chromop-

sin, the chemical reaction mentioned above occurs. A cone may have all

three types of chromopsins, but one type tends to predominate in any

single cone. The brain can thus interpret color as signals from a pat-

tern of cones. [67]

In the retina, the distribution of the rods and cones differ. In

the periphery, the rods dominate. As one moves more centrally, the rela-

tive number of cones increases. In the macula, the visual center of the eye, there is virtually only cones. There are other anatomic differences as well. The cones are packed more densely and are smaller in diameter than the rods. There are even differences among the cones, with the more central ones being smaller and more densely packed than the peripheral ones. As will be seen later, this aids in visual acuity. The other major anatomic difference is synaptic ratio with the bipolar cells. [64] The centrally located cones synapse 1:1 with the bipolar cells, and are ultimately represented individually in the cortex. As one moves more peripherally, a larger number of primary receptor cells synapse with each bipolar cell. Finally, when one reaches the periphery, there may be as many as seven rods synapsing with each bipolar cell. This synaptic ratio plays an important part in both night vision and visual acuity.

VISUAL ACUITY

Visual acuity can be defined as the minimal separable distance between two targets that can be perceived, [23] that is, the minimum resolvable threshold is the ability to perceive two adjacent and simultaneously observed objects as being separate. [64]

Measurement of visual acuity is based on work done by Snellen. [68] His work is based on the emperical observation made by Robert Hooke in 1705 that in order for the normal eye to discern two stars, the stars must subtend a minimum angle of one minute of arc. [69] The resultant 20/20 visual acuity was thus defined by Snellen as the acuity required to perceive two targets that were separated by one minute of arc. A visual acuity of 20/40 would be the acuity required to perceive two targets that were separated by two minutes of arc. Thus, the separation

of the two targets, in minutes of arc, would be the reciprocal of the visual acuity. The actual definition of 20/n visual acuity, as given by Snellen, is the acuity at which two objects, which subtend an arc of one minute at n feet, can be perceived as separate at 20 feet. He felt that a distance of twenty feet was necessary to remove interfering factors such as accommodation.

Other methods of denoting visual acuity are Snellen fraction and Snellen-Sterling visual efficiency. The Snellen fraction is merely the visual acuity interpreted as a fraction, i.e., 20/20 visual acuity is a 1.0 Snellen fraction, 20/40 is 0.5, 20/200 is 0.1, and so forth. The Snellen-Sterling visual efficiency [64] is defined as:

$$E = 0.836^{(1/S - 1)} \times 100$$

where E = visual efficiency in percentile

and S = The Snellen fraction

For a visual acuity of 20/20, $E = 100\%$, for 20/40, $E = 83.6\%$, for 20/200, $E = 19.9\%$ and so forth.

The standard method of measuring visual acuity is with the Snellen E or the Landolt C. The Snellen E occupies a five by five matrix, where unity is the subtended arc to be measured. In the Snellen E, each line (the back and the three arms), subtends one unit of arc being measured, and the distance between the arms (i.e., each of the two empty spaces) subtends one unit of arc (See Figure 3A). The Landolt C also occupies a five by five matrix. It is an almost complete circle, the width of the stroke of the letter subtending one unit of arc. The opening, forming the C, also subtends one unit of arc (See Figure 3B).

The visual acuity across the retina varies; it is a function of a number of different factors. The primary factor is the rod and cone

A

|←S·→|←S→|←S→|←S→|←S→|

5S

5S

S=1 SNELLEN
FRACTION IN
MINUTES OF ARC

B

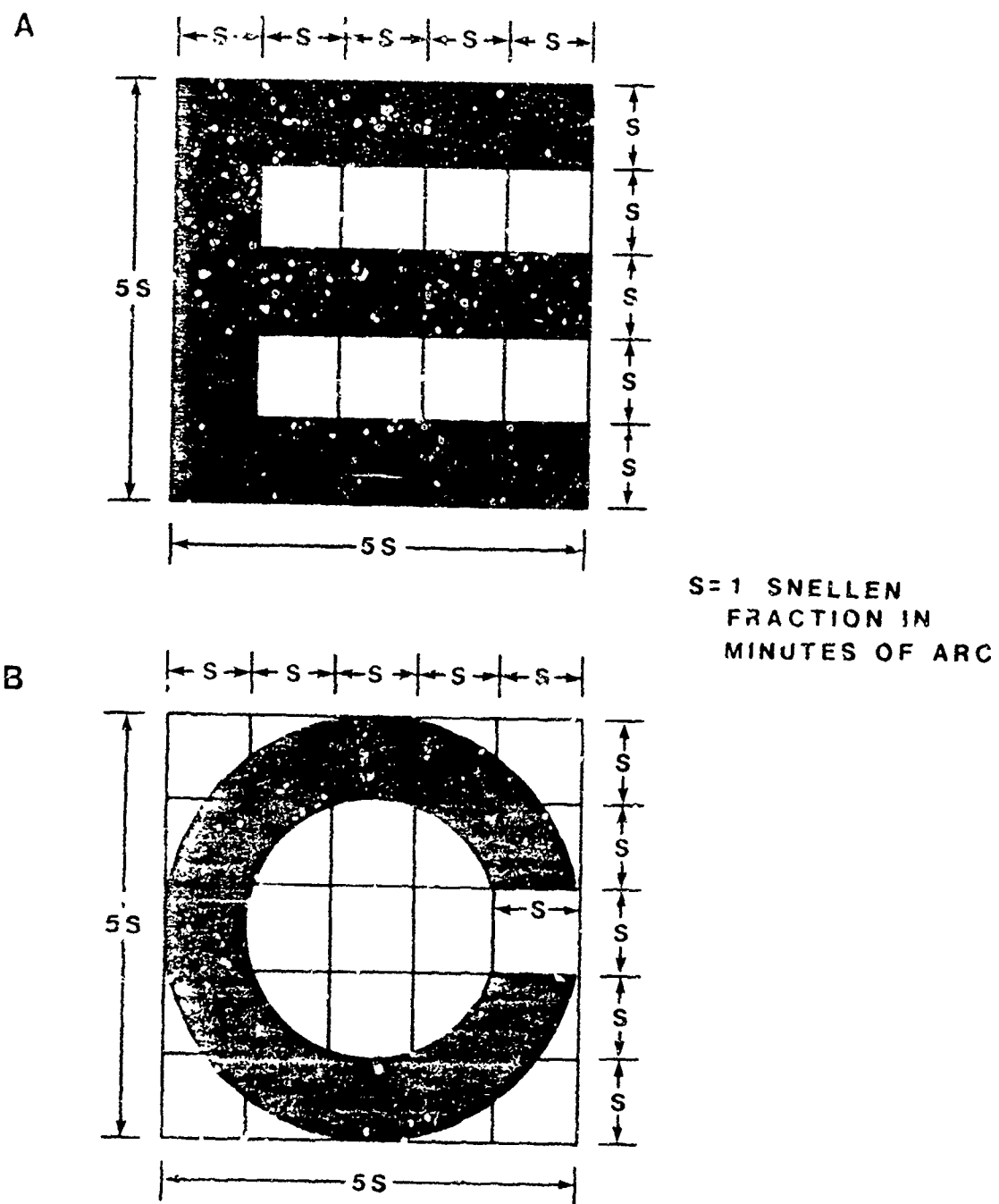|←S→|←S→|←S→|←S→|←S→|

5S

5S

Figure 3. A) SNELLEN E.   B) LANDOLT C

distribution. Cones have better visual acuity than rods. This is because they are smaller, more densely packed, and have a lower synaptic ratio with the bipolar cells (the cones in the center of the macula having a 1:1 synaptic ratio). These features allow small stimuli with minimal separated distances to activate two cones with an unstimulated cone between. Furthermore, the 1:1 synaptic ratio allows the brain to identify the specific area the stimulus activated. The best possible theoretical detail resolution, with the smallest, most densely packed cones in the center of the macula, is 30 seconds of arc, which corresponds to 20/10 visual acuity. The rods, being larger, less densely packed, and multiply represented on bipolar cells, have very poorly defined resolution capabilities. The best possible rod vision is 20/200, which corresponds to a 20% visual efficiency.

The other major retinal factor in visual acuity is the layer of secondary neuronal cells through which the light must pass before striking the rods and cones. This scatters the light somewhat, and significantly reduces the acuity. To partially eliminate this factor, there is an area at the center of the macula called the fovea where these secondary neurons fold back allowing this one small area (about 200 microns in diameter) to have a clear, unobstructed pathway of light. Only in the fovea is visual acuity of 20/20 or better possible. At 1° from the fovea, maximum acuity is 20/30, 20/70-100 at 5°, and 20/100-160 at 10°.

There are four other major factors which affect visual acuity.[59-65,67] The first is the optics of the non-diseased eye. This would include refractive errors, abnormal eyeball shape, transmission properties of the eye, optical aberrations, pupillary diameter, and so forth. These various factors can combine to give a wide range of acuity capa-

bility to a population.

The second factor is disease or injury states of the eye. This could include neuronal disease (eg., optic atrophy), ocular muscle disease, corneal or lenticular opacifications, vitreous inclusion bodies, retinal detachments, abnormalities of blood supply (eg., arteriosclerotic disease), retinopathies (eg., diabetic retinopathy and hypertensive retinopathy), thrombi, abnormalities of rods or cones, and many others.

The third is environmental (endogenous and exogenous) factors, and would include hypoxia, carbon monoxide poisoning, metabolic poisons, and similar factors which could adversely affect the oxygen sensitive receptor cells in the eye.

The final aspect affecting visual acuity is physical factors related to the stimulus variable. These would include target size and context, illumination, light wavelength, contrast, exposure or viewing time, air clarity, distances to target, relative angular velocity of target [70-73] (with respect to viewer), and so forth. All these factors together combine to significantly affect visual acuity. All of these factors, of course, require intact cerebral visual functions.

NIGHT VISION AND DARK ADAPTATION

Vision can be subdivided into three categories: photopic, mesopic and scotopic. [59-65,67] Photopic vision occurs in the approximate range 10^0 to 10^5 millilamberts, mesopic vision in the range 10^{-3} to 10^0 millilamberts, and scotopic vision in the range 10^{-6} to 10^{-3} millilamberts. Photopic vision consists of pure cone function, scotopic of pure rod function. Mesopic is the range of overlap in which both rods and cones are functioning. It is important to realize that in the mesopic range, there are two distinctly different processes going on, one a rod process,

the other a cone process. In other words, rods have a functioning range of 10^{-6} to 10^{0} millilamberts. Below 10^{-6} millilamberts, there is not enough ambient light to stimulate the receptors. Above 10^{0} millilamberts all of the rhodopsin is bleached out, resulting in a continual "on" signal from the rod. This continual "on" signal is subsequently ignored by the brain. [67] (This is the phenomenon responsible for the fading out of a dim light fixed on the retina. This is why one must use scanning technique during scotopic conditions). The cone has a functioning range of 10^{-3} to 10^{5} millilamberts, these limits being determined similarly to the rod limits, with the major exception of no fade out phenomenon in the cones. The overlap of the two is what we conveniently call mesopic vision, but, in reality, it is two distinct functions.

There are a number of theoretical reasons for the greater light sensitivity of rods. First, the rhodopsin tends to be more easily broken down, and, thus, more easily stimulated than the chromopsins. Second, the rhodopsin is affected by a much wider wavelength band than the chromopsins, thus making stimuli likely to set off a much larger number of rods than cones. The third reason is related to the synaptic ratio of rods to bipolar cells. When light intensities are low, small numbers of chemical reactions might be going on in the rods and cones, but not enough to fire off the nerve. However, if the rods are slightly stimulated, the summation of several low level stimuli may be enough to excite a bipolar cell, thus sending a "light" signal to the brain.

It is clear that under extremely low luminance conditions (i.e., scotopic conditions) the importance of the rods dominates. There are, however, some major drawbacks with the rod system. These include lack of visual acuity (20/200 at best), lack of color vision [74] and discrimi-

nation, lack of size and distance judgment,and ambiguity as to exact direction of stimulus (due to multiple rod synapses on each bipolar cell). As the light intensity increases, and the mesopic range is entered, the particular system utilized depends on task requirements (i.e., high acuity tasks, color discrimination tasks, etc., would involve the cone system; movement tracking tasks and light identification tasks would involve the rod system). The ability of the cones to respond to visual acuity tasks would be a function of the luminance level. In mesopic and photopic conditions, visual acuity increases in almost direct proportion to the logarithm of the luminance [23] ; however, under scotopic conditions, visual acuity is extremely insensitive and increases only slowly as luminance levels are raised from threshold. In scotopic conditions, the macula, which consists of only cones, becomes a functional blind spot.

Dark adaptation [13,16,18-28] is a process by which the eye adjusts from a high luminance setting to a low luminance setting. The exact mechanisms behind dark adaptation are unclear, but they are known to include physical, neuronal, and biochemical aspects such as pupillary dilitation, a resetting of neuron sensitivity, and a regeneration of visual pigment respectively. [20,23,64] The dark adaptation luminance threshold curve is a biphasic asymptotic curve (See Figure 4). The first phase of the curve is a rapid, but limited, cone dark adaptation limb. It requires 7-10 minutes, and approaches a limit in the mesopic range. The second limb of the curve is due to rod function which requires 30-45 minutes to effectively reach its limit which is in the scotopic range. As previously noted, the rods are relatively insensitive to red light. Approximately 20-30 minutes of the dark adaptation of the rods
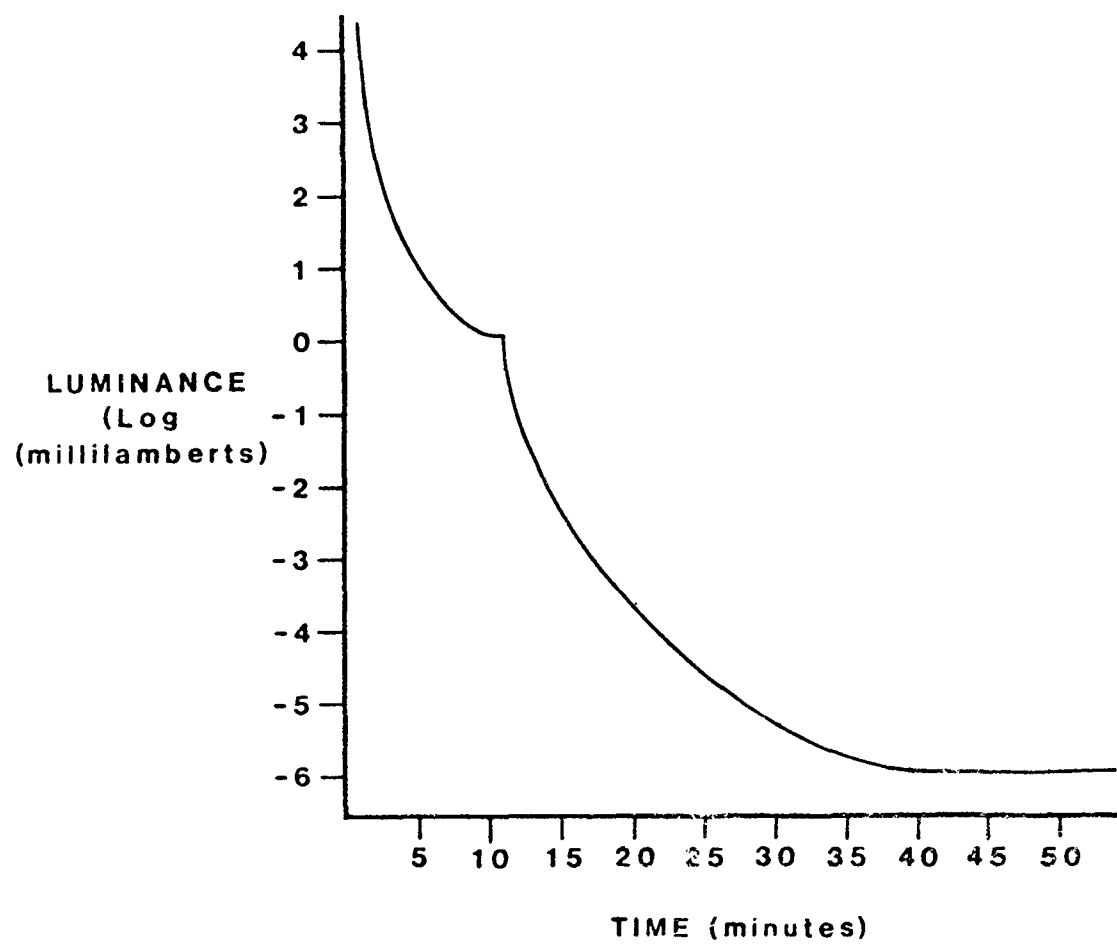
Figure 4. TYPICAL DARK ADAPTATION CURVE

can be achieved by wearing red goggles, or being exposed to only red light. [12-14,16-18,31,32,59,60] These methods have been employed in pilot ready rooms to help eliminate some of the time necessary to achieve full dark adaptation in an emergency situation. The actual luminance limit of cone or rod visual function is very variable in its time rates of adaptation, and in its absolute final threshold level among individuals and in the same individual at different times. There is, however, a greater variability in rod than in cone function at final threshold. Furthermore, tests have shown that mesopic and scotopic visual ability are not well correlated. That is, a person's inability to perform low luminance rod tasks (in the scotopic range) do not necessarily preclude his ability to perform low luminance cone tasks (in the mesopic range), and vice versa.

There are a number of conditions which affect night vision and dark adaptation. Some affect rods more, some cones more, and some both equally or indiscriminately. Some effects are deleterious, some beneficial. A number of these are outlined below (from reference 23 and/or 64 unless otherwise noted).

    A. Genetic factors - there are familial, non-environmental aspects of night vision ability.

    B. Somatic Factors

        1. A number of dioptric factors are associated with night vision ability. They include refractive powers, accommodation, pupillary diameter, phorias, and problems of eye fixation.

        2. Age - the major correlation is with lenticular opacification and loss of accommodation. There are also

the statistical associations of chronic disease
states such as diabetes and hypertension and their
associated retinopathies.

3. Variations in vitamin A metabolism

   a. Vitamin A malnutrition - inadequate intake,
      gastrointestinal losses

   b. Vitamin A transport or storage deficiencies -
      liver disease, protein malnutrition, tuberculosis

4. Disease states - retinitis pigmentosa, albinism,
   corneal opacities, lenticular opacities, optic atrophy,
   macular degeneration, arteriosclerotic retinopathy,
   diabetes retinopathy, hypertensive retinopathy

5. Pharmacology

   a. mydriatics will enhance night vision.

   b. caffeine enhances night vision.[75]

   c. amphetamines questionably enhance night vision
      (they are known to improve associated motor tasks).

   d. miotic drugs inhibit night vision.

   e. ethanol raises threshold levels.

   f. phenothiazines and antimalarials can cause retino-
      pathies and adversely affect night vision.

   g. psychotropic drugs and tranquilizers inhibit night
      vision.

   h. metabolic poisons - drugs that cause CNS hypoxia,
      regional blood flow restrictions to the brain, or
      changes in the oxidative process have adverse
      effects on night vision threshold.

C. Behavioral aspects - motivation, experience, training, and stress all have variable effects on night vision.

D. Environmental Factors

    a. climate - rain, fog, haze, etc., can affect night vision capabilities.

    b. preadaptation exposure - prolonged exposures to high luminance situations prolongs rates of adaptation and increases final adaptive threshold.

    c. Oxygen levels - night vision is probably the most hypoxia sensitive system in the body. [23,64,76-79] In the laboratory, rods have been shown to be significantly affected at alveolar oxygen tensions of seventy five millimeters of mercury. Cones are much less affected, requiring alveolar oxygen tensions of forty millimeter of mercury before deleterious effects could be demonstrated.

    d. Altitude - this is primarily a function of lowered alveolar oxygen tensions.

    e. Carbon dioxide - air levels as low as 1.5% have been shown to decrease night vision sensitivity.[80]

    f. carbon monoxide - the deleterious effect is primarily due to displacement of oxygen.

    g. cyanide - poisons cellular respiration and inhibits night vision.

    h. ozone - decreases visual acuity and possibly affects night vision.

    i. Hypotension - reduces effective blood supply to eye

and decreases visual acuity and night vision.[81]

This overview of potential factors that affect night vision is by no means exhaustive, but it highlights many of the major factors.

ACCELERATION AND VISION

There are a number of different types of acceleration, including impact type acceleration, deceleration, linear sustained acceleration, and angular acceleration. This paper will consider only linear sustained acceleration.

Linear sustained acceleration is the inertial reaction to a resultant unidirectional force with time duration above approximately 0.2 seconds.[52] It is important to differentiate t' inertial physiological acceleration, denoted G, from the true displacement acceleration, denoted g. The physiological acceleration represents the inertial reactive force and is in the opposite direction of the true displacement acceleration. The G forces can be divided into three planes, x, y, and z. The various directions and terminologies are summarized below.[54]

True Displacement Acceleration	Direction of Resultant Inertial Force	Vernacular Discriptive	Standard Terminology
Headward	Head to foot	Eyeballs down	+Gz
Footward	Foot to head	Eyeballs up	−Gz
Forward	Chest to back	Eyeballs in	+Gx
Backward	Back to chest	Eyeballs out	−Gx
To the right	Right to left	Eyeballs left	+Gy
To the left	Left to right	Eyeballs right	−Gy

The physiological effects of acceleration are myriad.[36,39-58,82] Only the effects pertaining to vision will be examined. It is important to remember that G-tolerance levels depend upon direction, duration, and

magnitude of the G vector. [55] Other important factors are rate of G on-
set and decay, endpoint of tolerance selected, environmental conditions
present, anti-G mechanisms used, body positioning, and the motivation,
conditioning, and training of the subjects. Furthermore, there is signi-
ficant individual variation in G tolerance. The many works done on
physiological effects of acceleration and on G-tolerance are often not
standardized; this must be taken into account when interpreting G values
and their application to specific situations.

The vast majority of work has been done on +Gz acceleration. The
classic +Gz effects on acceleration are grey-out, the inability to see
a light stimulus in the peripheral field of view, blackout, a complete
loss of vision, and unconsciousness (not a visual symptom). These phys-
iological symptoms are a function of blood pressure, pulse pressure,
heart-brain distance, and intraocular pressure.

The normal intraocular tension is about twenty-one millimeters of
mercury. The central retinal artery (CRA) pressure must be greater than
this to supply blood to the eye. The CRA pressure is the difference
between the systemic blood pressure and the hydrostatic pressure exerted
by the heart-brain distance. The blood supplied to the CRA enters the
fundus of the eye in the area of the optic disc and flows peripherally
into ever decreasing areas of pressure. The blood flow can be effec-
tively reduced by four methods: reducing blood pressure (hypotensive
states), increasing intraocular pressure (eg., glaucome), increasing
heart-brain distance (standing erect), or increasing the hydrostatic
pressure on the column of blood (hypergravic states). As the relative
pressure of the CRA is reduced, the flow pressure across the retira is
reduced. Since the periphery of the eye has the lowest arterial pres-

sure, it is the first to be affected. When this occurs, grey-out begins. The subject, if the situation continues, will get a progressive, fairly concentric, narrowing of the visual field. Finally, if the relative pressure is reduced far enough, the subject experiences central visual loss, blackout.

The actual mechanism of visual loss is not lack of blood flow, per se, but the loss of oxygen and metabolites supplied by the blood. There is, therefore, a five to six second lag period between loss of blood supply and loss of visual ability. Also, the visual loss phenomenon is not a purely on and off situation, but one of gradually reduced sensitivity as the absolute blood flow is reduced. This is indicated by studies which show that lower G levels achieve grey-out and blackout when lower luminance levels are used; as the luminance levels are increased, higher G levels are necessary to cause grey-out and blackout. There is a point reached, however, when, upon total loss of blood flow, no light stimulus evokes a visual response. These luminance factors must be taken into account when values indicating levels of grey-out or blackout are used.

The visual effect of $-Gz$ is primarily a phenomenon called "red out". Its basis is contraversial; it is apparently due either to blood engorgement of the anatomical structures of the eye, or to displacement of the lower lid over the cornea (this latter theory is presently favored). This causes the subject to perceive his surroundings through a progressively darker red hue until, finally, the whole visual field is obliterated by red out.

The visual effects of $\pm Gx$ (transverse acceleration) are physical, related to corneal tearing and displacement of anatomic structures, such

as the lens. The primary symptomatic tolerance limits of the Gx environment are related to muscular inadequacy, which is reached before significant alteration of visual physiology occurs.

Exploration of the Gy environment is relatively new; only recently have technological advances in aerodynamic hardware made such a study rewarding in a practical sense. To date, no specific measurements of visual physiology have been undertaken in the Gy environment. In a related development, however, recent work has shown a significant reduction in arterial oxygen saturation, probably secondary to regional shifts in pulmonary ventilation and perfusion. [83] This relative hypoxia could, theoretically, significantly affect the highly oxygen sensitive visual system. As the relative oxygen requirements of the visual system have been shown to be related to luminance levels, the scotopic and mesopic visual ranges may be the most significantly affected.

IV. MATERIALS AND METHODS

EXPERIMENTAL PLAN

The experiment was designed to explore any shift in visual threshold at 20/50 acuity in various linear sustained acceleration environments. Visual acuity of 20/50 simulates normal aircraft instrument lettering size. [84] The 20/50 visual acuity requirement effectively reduces the task to a measurement of cone only function.

This would simulate a situation in which a pilot was relying on his instruments during night flight. In order to maintain maximum out of aircraft night vision capabilities and to risk minimum detection probability in a combat situation, the pilot will usually decrease the luminance levels on the dials or readouts to virtual minimum for readability.

If a higher G environment is suddenly encountered, either via combat or evasive maneuvers, the pilot may lose sight of his instruments if there is a true shift in visual threshold levels.

The +Gz environment is known to cause profound visual symptoms at relatively high levels; in this study, lower Gz values (+3Gz maximum) were chosen to examine the more subtle effects which might occur with the low luminance levels used.

The $\pm$Gx environment causes relatively few visual effects, it was therefore felt that studies in this field would be relatively unproductive. A +1Gx static test is performed for control purposes.

The visual effects of the Gy environment are virtually unknown. They are examined in this paper up to +2Gy.

In this paper, no studies are done in the -Gz or -Gy environment. The -Gz environment has no significant physiologic visual symptoms; it was felt that such studies would have been unproductive at this point. While some recent work indicates there are differences between the +Gy and the -Gy environment, [83] it was felt that they were similar enough to examine only one of these in this initial study.

CENTRIFUGE

All G exposures were conducted on the Dynamic Environment Simulator (DES) located at the United States Air Force Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio. The centrifuge has a radius of twenty feet. It is capable of motion in all three axes and is able to simulate the three G vectors independently or combined. The profiles are controlled and duplicated using a Sel 32/77 digital computer. The subjects were seated in the cab in an ACES-II Seat (Advanced Concept Ejection Seat) with a seat back angle of thirty degrees. Shoul-

der restraints are mounted on either side of the seat to provide lateral support and restrict lateral movement.

SUBJECTS

Eleven male human subjects were used. All are members of the United State Air Force and part of a volunteer group for centrifuge acceleration experiments. All are well adapted to the DES acceleration. The voluntary informed consent of the subjects used in this research was obtained in accordance with AFR 169-3 and Wright State University regulations concerning research involving human subjects. All of the subjects had passed a flight physical exam. Their ages ranged from 25 to 39 years (mean $\pm$ SD, 28.9 $\pm$ 4.1 years), and they weighed 140 to 200 pounds (174.6 $\pm$ 18.2 lb.). Their heights were 66.5 to 74 inches (70.8 $\pm$ 2.6 ins.). Three of them wore only glasses, none wore only contacts, and none wore glasses and contacts. Eight wore neither glasses nor contacts. All subjects had 20/20 vision, or vision corrected to 20/20. Each subject wore the standard USAF flight suit; the subjects did not wear anti-G suits.

Because of the potential affects of alcohol, tobacco, medications, and caffeine on night vision, subjects were asked to refrain from the use of these products for eight hours prior to the experimental run. As glucose loading has also been shown to have an affect on this parameter, light breakfasts of toast, danish, or cereal, and milk or juice was advised.

The subjects were partially pre-dark adapted with dark red goggles, which filtered out all wavelength less than 610 nm. During this time, they were suited up, appropriate monitoring equipment was fitted, and the subject was placed in the cab. After this, the lights in the cab

and the DES room were turned off. This resulted in an ambient luminance of .01 millilamberts, which approximates normal night cockpit luminance. At this time, the subject removed his goggles and underwent an additional ten minutes of dark adaptation before experimental runs began.

PERFORMANCE TASK

A 1x1 1/8 inch black and white 510 line video monitor was mounted in the cab 44 inches from the subject. A Snellen E was projected in one of four attitudes (prongs up, prongs right, prongs down, prongs left) by an Apple II Plus computer. The Snellen E total size was 4.06 millimeters, which, at 44 inches, subtends an arc of 2.5 minutes in a 5x5 matrix and produces a 20/50 visual acuity measurement. The luminance of the letter ranged from 0.00037 to 0.154 millilamberts (produced by a control voltage of 2.00 to 4.35 volts); it increased in 40 discrete steps over 36 seconds. The control voltage was continuously recorded and averaged every 1 second over the 36 second profile. This resulted in a reproducible average control voltage and a corresponding luminance (See Table 1). When the subject could identify the direction of the prongs of the E, he would make the appropriate movement on a force stick controller. The E direction was completely randomized within and between subjects.

ACCELERATION PROFILE

The subject first performed twelve static runs at +1Gz. In this group of tasks, the subject had the E direction pseudorandomized with three each in the four possible directions (the subject was told the E was completely randomized so he would not try to discern a pattern). The purpose of these runs was to eliminate a learning curve which might result during the actual runs. It was felt that the subject had already

TABLE 1

Output Average Voltage and Corresponding Luminance

and Contrast Levels

| Second | Voltage | Luminance (millilamberts) | | Contrast(%) | Log Luminance |
		F	Background		
1	2.00	.00037	.00037	0	-3.430
2	2.07	.00037	.00037	0	-3.430
3	2.13	.00037	.00037	0	-3.430
4	2.20	.00037	.00037	0	-3.430
5	2.27	.00037	.00037	0	-3.430
6	2.33	.00037	.00037	0	-3.430
7	2.42	.00037	.00037	0	-3.430
8	2.48	.00046	.00037	11.0	-3.333
9	2.55	.00093	.00046	33.3	-3.032
10	2.62	.00121	.00046	44.4	-2.918
11	2.68	.00167	.00074	38.5	-2.777
12	2.75	.00232			-2.634
13	2.83	.00455			-2.342
14	2.90	.00827	.00084	81.6	-2.083
15	2.97	.0177			-1.753
16	3.03	.0344			-1.464
17	3.10	.0641	.00139	95.7	-1.193
18	3.17	.0994			-1.003
19	3.25	.125			-0.902
20	3.32	.138	.00167	97.6	-0.859
21	3.38	.140			-0.853
22	3.45	.144			-0.842
23	3.52	.145	.00167	97.7	-0.839
24	3.58	.146			-0.836
25	3.67	.146			-0.836
26	3.73	.147	.00177	97.6	-0.833
27	3.80	.148			-0.831
28	3.87	.149			-0.828
29	3.93	.149	.00177	97.7	-0.828
30	4.00	.150			-0.825
31	4.08	.151			-0.820
32	4.15	.152	.00177	97.7	-0.817
33	4.22	.153			-0.815
34	4.28	.153			-0.815
35	4.35	.154	.00186	97.6	-0.812

All responses were between control voltages 2.42 and 3.32. In this range, the log luminance was linearly correlated with voltage with slope = 3.163, y-intercept = -11.18 and correlation coefficient, r^2 = .9923. This is an ideal condition because in mesopic conditions, visual acuity increases in almost direct proportion to the logarithm of the luminance.[23]

learned any subtle differences in E direction by the end of these twelve static runs. Each run lasted 36 seconds with 5 seconds between runs.

The subject next performed the task during three static control runs at 1 Gx, 1 Gy, and 1 Gz (cab rotated 60° back, 90° left, and upright, respectively). The order of these runs was randomized. Following this, the subject was brought to +1.4Gz baseline and the performance task was again completed. Each run lasted 36 seconds with 90 seconds between runs. The 90 seconds was considered adequate to re-dark adapt.

The experimental runs consisted of nine profiles, three each at +2Gz, +3Gz, and +2Gy at +1Gz. The nine runs were completely randomized within and between subjects. Each run lasted 36 seconds with 90 seconds between runs. The 90 second re-dark adaptation period during the experimental runs was at baseline, 1.4 Gz. (See Table 2 for example of randomized plan of acceleration exposures and E attitudes).

The 36 second runs were preceded by 10 seconds of acceleration to the exposure level and followed by 10 seconds of deceleration to the 1.4 Gz baseline (See Figure 5). Each subject ran two days with at least one days rest between runs.

MONITORING EQUIPMENT

All subjects were instrumented with standard EKG leads and ear oximeter with head mount strap (Hewlett-Packard Model 47201A). Heart rate and oximeter read-out of PaO_2 were continuously recorded and averaged every 1 seconds over the 36 second profile. These values were printed at the end of every run by the Sel 32/77.

STATISTICS

For the training data, analysis of variance (ANOVA) were performed separately on data obtained from the ear oximeter (PaO_2), heart rate

TABLE 2

Example Randomization Schedule – All G Values are +

|	Subject A				Subject B		
Day 1		Day 2		Day 1		Day 2	
G-profile	E direction	G-profile	E direction	G-profile	E direction	G-profile	E direction
1Gz	Up	1Gz	Up	1Gz	Left	1Gz	Down
1Gz	Up	1Gz	Down	1Gz	Up	1Gz	Left
1Gz	Left	1Gz	Left	1Gz	Left	1Gz	Down
1Gz	Up	1Gz	Down	1Gz	Right	1Gz	Left
1Gz	Down	1Gz	Down	1Gz	Down	1Gz	Right
1Gz	Left	1Gz	Left	1Gz	Up	1Gz	Left
1Gz	Right	1Gz	Left	1Gz	Left	1Gz	Up
1Gz	Down	1Gz	Right	1Gz	Down	1Gz	Up
1Gz	Right	1Gz	Right	1Gz	Down	1Gz	Right
1Gz	Right	1Gz	Right	1Gz	Up	1Gz	Right
1Gz	Left	1Gz	Up	1Gz	Right	1Gz	Down
1Gz	Down	1Gz	Up	1Gz	Right	1Gz	Up
1Gx	Up	1Gy	Right	1Gz	Left	1Gx	Right
1Gz	Up	1Gz	Up	1Gy	Right	1Gv	Left
1Gy	Up	1Gx	Left	1Gx	Right	1Gz	Right
1.4Gz	Right	1.4Gz	Up	1.4Gz	Right	1.4Gz	Left
2Gz	Down	3Gz	Right	3Gz	Up	3Gz	Left
2Gv	Left	2Gz	Up	2Gy	Up	2Gy	Right
2Cy	Down	3Cz	Down	2Gz	Left	3Gz	Down
3Gz	Left	2Gy	Down	2Cz	Up	3Gz	Right
3Gz	Right	2Gy	Up	2Gz	Down	2Gz	Right
2Gz	Left	2Gy	Right	2Gy	Left	2Gy	Down
3Gz	Up	2Gz	Down	3Gz	Right	2Gv	Right
3Gz	Up	3Gz	Left	3Cz	Left	2Gz	Up
2Gz	Up	2Gz	Down	2Gy	Down	2Gz	Right
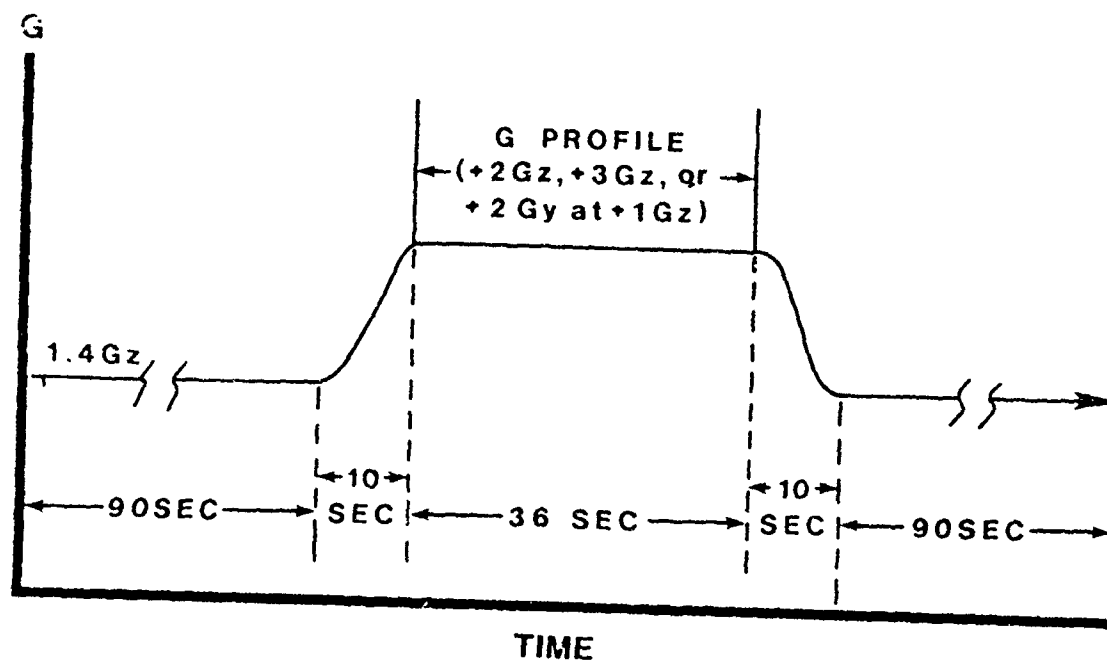
Figure 5. ACCELERATION PROFILE

(HR) response, and log luminance (LUM) task response. (Note: analysis was done versus log luminance because in the mesopic range visual acuity is directly proportional to the log of the luminance.)

The experimental data was analyzed by comparison of means with self paired two tailed t-test, with nine degrees of freedom, at a significance level of 0.05.

V. RESULTS

Each subject was exposed to seven different G combinations (+1Gz, +1Gy, +1Gx, +1.4Gz, +2.0Gz, +3.0Gz, and +2.0Gy at +1.0Gz), for each of two days. Analysis of the training data (at +1Gz) indicated there was a statistically significant difference between luminance response and E direction. This was due to properties of the CRT which slightly altered the shape of the E depending upon its attitude (prongs up, prongs right, prongs down, prongs left). To eliminate this effect, each individual's pre-exposure control value of the same E direction was used as his own zero point and the subsequent levels were either + or - from this point. This was done by taking all the +1Gz runs of the subject on any particular day (training and experimental). The subject's best results (i.e., his most trained state with the least extraneous influences) in each of the four E directions were taken as the control values for that subject for that day. Zero means were then determined using the control matched for E direction.

Subject 1 did not perform training data; he therefore, did not have adequate control data for further zero mean analysis. He was eliminated from the study.

Initial analysis revealed there was no statistically significant

difference between day 1 and day 2 between any of the parameters at any G level involved. Therefore, the two days of data were combined for further analysis. The next step revealed no difference between glass wearers and non-glass wearers, so these groups could be combined.

Analysis models included the following test hypothesis:

Ho: There is no difference in the parameter being examined (PaO_2, HR, or LUM) between the G-level being examined and the +1Gz control level.

The resultant zero means are summarized in Table 3, the statistical analysis of the experimental data is summarized in Table 4.

VI. DISCUSSION

The prime concern of this work is examination of the luminance changes, however, a number of other factors which may affect these parameters must first be examined. Some of these effects can be eliminated, effectively simplifying our resultant model.

A. INDIVIDUAL VARIATION

Mesopic and scotopic vision is frequently subject to large individual variation with respect to absolute threshold values. This experiment was no exception with the mesopic threshold for 20/50 visual acuity ranging from .00037 to .138 millilamberts. To eliminate this factor, zero means were used. Each subject was his own control each day, therefore, the individual variation was for the most part eliminated.

Furthermore, in a real fighter aircraft situation, the crew member can set the luminance levels on the dials and readouts to his own virtual minimum for readability. Thus, it is the shift in threshold, not the actual threshold, which one is concerned with.

TABLE 3

Summary of Zero Means

G-level	HR	PaO$_2$	LUM
+1Gv	+0.915 SE = 1.124	+0.160 SE = 0.131	+0.145 (1.396) SE = 0.131
+1Gv	−1.595 SE = 1.857	+0.0885 SE = 0.157	+0.3195 (2.087) SE = 0.131
+1.4Gz	+1.855 SE = 1.331	+0.301 SE = 0.121	+0.122 (1.324) SE = 0.072
+2.0Gz	+5.045 SE = 1.423	−0.5525 SE = 0.162	+0.300 (1.995) SE = 0.064
+3.0Gz	+18.59 SE = 4.677	−0.7795 SE = 0.198	+0.442 (2.767) SE = 0.071
+2.0Gy at +1.0Gz	+5.07 SE = 0.731	−1.4395 SE = 0.306	+0.3295 (2.136) SE = 0.063

HR = Heart rate (beats per minute)

PaO$_2$ = Arterial oxygen partial pressure (millimeters of mercury)

LUM = Log luminance (log millilamberts) − the number in parentheses

is the multiplicative factor in absolute luminance

SE = Standard error

TABLE 4

Summary of Statistical Analysis

G-level	HR	PaO$_2$	LUM
+1Gy	NS	NS	NS
+1Gx	NS	NS	p<.05 increased luminance at G
+1.8Gz	NS	p<.05 increased PaO$_2$ at G	NS
+2.0Gz	p<.01 increased HR at G	p<.01 decreased PaO$_2$ at G	p<.01 increased luminance at G
+3.0Gz	p<.01 increased HR at G	p<.01 decreased PaO$_2$ at G	p<.01 increased luminance at G
+2.0Gy at +1.0Gz	p<.01 increased HR at G	p<.01 decreased PaO$_2$ at G	p<.01 increased luminance at G

NS = Not statistically significant

HR = Heart rate (beats per minute)

PaO$_2$ = Arterial oxygen partial pressure (millimeters of mercury)

LUM = Log luminance (log millilamberts)

This experiment not only simulates this aspect of the real situation, it also effectively eliminates the individual variation as a variable.

B. DAILY VARIATION

Not only is there a mesopic and scotopic variation between individuals, but there is also variation in the same individual on different days. This experiment demonstrated this expected night vision phenomenon. Again, this variable was eliminated by zero means and can be ignored. As described in the results section, statistical analysis of zero means between day 1 and 2 showed no significant difference at the .05 level.

C. GLASSES

The wearing of glasses could feasibly affect the experiment for three reasons. First, the addition of an additional lens system could reflect enough light to shift threshold values (typical glasses reflect 4-8% of the incident light). Second, the abnormal distortion of the eyeglasses during G could move the focus point far enough from the retina to grossly distort the image. Third, the pathology associated with the need to wear glasses could theoretically be affected by G exposure.

Statistical analysis of zero means of glass wearers versus non-glass wearers showed no significant difference at the .05 level. For the purpose of this experiment, analysis eliminates glasses as a variable. Whether the wearing of glasses actually affects absolute mesopic vision threshold values is an interesting question. However, to tell whether any differences noted were truly due to wearing glasses or merely to individual variations would require much larger sample

sizes.

D. CARDIOVASCULAR EFFECTS

1. Heart Rate

As would be expected from the literature, the static environments
of +1Gy and +1Gx showed no significant changes in the heart rate. The
challenging +2.0Gz, +3.0Gz and +2.0Gy at +1.0Gz all showed very signifi-
cant changes in heart rate (p<.01). The +1.4Gz showed no significant
change in the heart rate. This, I feel, is due to the conditioning and
G experience of these subjects. A novice population would no doubt show
a change at this G level.

The blood supply to the eye is probably the major determining fac-
tor of mesopic vision threshold. Heart rate, of course, is a major
determinant of the absolute amount of blood that reaches the eye. The
significant rise in heart rate would tend, if anything, to partially
overcome any shift in luminance threshold values. Shifts that do occur
would be inspite of the changes in heart rate.

2. Blood pressure

This very important determinant of cerebral perfusion could unfor-
tunately not be performed in this experiment. The time necessary for
the available automatic blood pressure cuffs to give a reading was
much longer than the time from initiation of an experimental run to a
correct task response. Blood pressure readings, therefore, would not
necessarily have been representative of the blood pressure at time of
response.

If rapid, near instantaneous, non-invasive blood pressure monitor-
ing devices were available, they would be a very valuable aid in future
experiments of this type.

tilation) and the associated $PaCO_2$ level. This will be discussed under pulmonary effects.

E. HEAD MOVEMENT

Movement of the head caused by movement of the cab could feasibly distort the subjects ability to focus the E, and, thus, shift the luminance threshold value. This, however, is unlikely. First, the cab is very steady and the subjects report very little sensation of movement. Second, the study did demonstrate a luminance threshold shift at +1Gx (a static condition with no head movement), while there was no shift at +1.4Gz (a dynamic condition in which head movement was possible).

F. PULMONARY EFFECTS

1. Arterial oxygen partial pressure

There was no significant static changes in PaO_2 at +1Gy or +1Gx, as expected. Also as expected were statistically significant drops in PaO_2 during G runs at +2.0Gz, +3.0Gz and +2.0Gy at +1.0Gz. The changes in PaO_2 at +Gz are due, primarily, to accentuation of normal +1Gz ventilation-perfusion mismatch. The changes at Gy are less well explored, but have been consistently reported by Popplow [83] and others. It is thought to be due to a lateral shift of pulmonary fluids and gasses forming a lateral ventilation-perfusion mismatch.

Less easy to explain is the statistically significant increase in PaO_2 at +1.4Gz. There are three possible explanations for this rise. The first is a real rise in PaO_2. This is highly likely and easily explained by the alveolar oxygen equation:

$$P_AO_2 = F_IO_2 (P_B - P_{H20}) - \frac{P_ACO_2}{R}$$

P_AO_2 = alveolar partial pressure of oxygen

F_IO_2 = fractional content of oxygen (about 21%)

P_B = barometric pressure (about 760 mm Hg)

P_{H2O} = partial pressure of water (47 mm Hg at 37^0C)

$P_A CO_2$= alveolar partial pressure of carbon dioxide

R   = respiratory quotient (about 0.8)

Assuming $F_I O_2$, P_B, P_{H2O}, and R are constant, $P_A O_2$ would be negative-ly proportional to $P_A CO_2$, which is a function of ventilation. To raise the $P_A O_2$ from the normal 100 mm Hg to 102 mm Hg, one must drop the $P_A CO_2$ a mere 1.6 mm Hg. In this experiment, the PaO_2 was raised a mere 0.301 mm Hg. While it is true that the increased ventilation-perfusion mismatch which occurs at G would blunt this rise in PaO_2 caused by hyper-ventilation, perhaps at +1.4Gz it was not a great enough mismatch to totally overcome the effects.

A second explanation for the rise in PaO_2 could be a false reading due to an idiosyncracy of the ear oximeter at G. While possible, this is unlikely as the accuracy of the ear oximeter under various conditions has been verified by Saunders,[85] Cissik,[86] and others.

The third possible cause for a statistically significant rise in PaO_2 is a type I error, that is, erroneously rejecting a null hypothesis that is really true. Whenever one deals with statistics, this is a possibility which must be taken into account. The t value in this case was quite near the level of significance; this cause, therefore, cannot easily be ruled out.

The most important aspect of examination of PaO_2 in this instance, however, is not statistical significance, but rather, physiological significance. By examination of Table 3, one clearly sees that the absolute shifts of PaO_2 were quite small. Virtually never did the PaO_2 fall below 90 mm Hg in this experiment. At these levels, one would be

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unlikely to see any real effects. Rods are not significantly affected until the PaO_2 drops into the seventies. Cones are even less sensitive, possibly not affected until the PaO_2 drops into the forties. Hypoxia, therefore, is an unlikely cause of significant luminance threshold shifts.

2. Hyperventilation

There are two aspects of hyperventilation which can affect luminance threshold values. The first is the increased P_AO_2 associated with a decreased P_ACO_2. This, however, is unlikely to cause any significant physiological impairment. The other aspect, as alluded to in the section on cardiovascular effects, is the cerebrovascular constriction, and resultant decrease in retinal blood supply, associated with a decreased P_ACO_2.

Measuring a person's P_ACO_2, however, would not necessarily provide us with significant data. An individual's P_ACO_2 cannot necessarily be directly correlated to the relative decrease in retinal blood flow caused by cerebrovascular constriction. More useful information could potentially be obtained from retinal plethysmography. While this could not differentiate the effects of blood pressure, cardiac output, or cerebrovascular constriction, it could provide a correlate between retinal blood flow and mesopic luminance threshold shifts. Equipment compatable with this centrifuge experiment was not available to us at the time we were running. However, future experimentation could certainly benefit from its use.

G. LUMINANCE (See Tables 3 and 4)

There was no statistically significant change in mesopic luminance threshold at +1Gy or +1.4Gz. There was a statistically significant

increase in mesopic luminance threshold at +1Gx, +2.0Gz, +3.0Gz, and +2.0Gy at +1.0Gz; +1Gx at the .05 level, the others at the .01 level. These findings are both statistically and physiologically significant.

The changes at dynamic G are not due to individual variation, daily variation, glasses, or head movement, as previously explained. Heart rate and cardiovascular conditioning, if anything, would lower the threshold. The drop in arterial partial pressure of oxygen was physiologically insignificant. The significant factors are therefore most likely related to changes in retinal blood supply associated with lowered blood pressure, blood shifts to the lower extremities, reduction in cardiac output, and/or cerebrovascular constriction associated with hyperventilation.

In the +2.0Gz and +3.0Gz environment, the most likely phenomenon is blood shift to the lower extremities, though the other three can certainly not be ruled out. More work is necessary. Measuring luminance associations with blood pressure, fluid shifts, cardiac output, and retinal plethysmography would be necessary before this could be definitively worked out.

In the +2.0Gy environment, the situation is less clear. While the results leave little doubt of significance with p<.01, the cause cannot be determined without further work. Blood shift is probably not the answer here, though, as previously mentioned, testing of individual eyes could certainly be rewarding in the study of Gy physiology. It is more likely that reduced blood pressure, reduced cardiac output and/or cerebrovascular constriction is the cause of luminance threshold shifts.

The resultant significance in the +1Gx environment cannot easily be explained. Hypotension, blood shift, or reduced cardiac output are

unlikely in a static environment. While hyperventilation and resultant cerebrovascular constriction is possible, the resultant rise in PaO_2 one would expect to see is not evident. A more likely explanation is some human idiosyncracy in viewing the screen or responding to the task that was present in this G environment. Possibly a larger sample size would have eliminated this aspect of variation. Again, the t value was very close to the level of significance, and a type I error is possible.

VII. CONCLUSIONS

There seems to be a real and significant rise in mesopic luminance threshold at +Gz and +Gy. More work needs to be done to define the exact physiologic parameters associated with these changes. Possible fields of productive research would include blood pressure monitoring, measuring fluid shifts, measurement of cardiac output, retinal plethysmography, measurement of P_ACO_2 or $PaCO_2$ levels, and individual eye testing during +Gy and -Gy exposures.

The results of this work indicate that in a combat situation, the pilot could easily be exposed to a G load in which his mesopic luminance threshold undergoes a significant shift. If such low G levels, at the relatively high visual acuity level of 20/50, are so adversely affected, much higher G levels, or more stringent acuity requirements, would be expected to show an even greater shift. These factors must be taken into account when design engineers develop the lighting for aircraft. Automatic increases in luminance should be built in which adjust to the G load.

In addition to the work done in this experiment, and the potential future work suggested above, other areas of interest which should be

addressed include the effects of prolonged G load on luminance threshold values, threshold shifts during "recovery" from G-load, shifts associated with combined vector G loading, and the association between luminance threshold shifts and contrast sensitivity.

Clearly, much work remains before this field is fully explored and developed. The importance of this work, from a crew safety standpoint, accentuates the need for further study in this field.

APPENDIX A

Glossary

accomodation - The automatic adjustment of the eye for seeing at
   different distances effected chiefly by changes in the convexity
   of the crystalline lens.

albinism - An inherited deficiency or absence of pigment in the skin,
   hair, and eyes due to tyrosene abnormality in production of
   melanin.

angular acceleration - The rate of change of direction of motion with
   respect to time.

candle - The primary measure of luminance. It equals one-sixtieth of
   the luminous intensity coming from one square centimeter of plati-
   num at its freezing point.

choroid - The middle, vascular tunic of the eye lying between the retina
   and the sclera.

contrast - Comparison of the luminance of an object (Lo) with respect
   to the background luminance (L_B) where percent contrast equals

$$\frac{Lo - L_B}{Lo + L_B}$$

deceleration - The rate of decrease of velocity with respect to time.

impact acceleration - Linear acceleration or deceleration of duration
   less than 1.0 seconds (time frame may vary depending on the source
   referred to).

macular degeneration - Atrophy of the macula of the retina.

mesopic vision - The luminance range, approximately 10^{-3} to 10^{0} milli-
   lamberts, which involves both rod and cone function.

millilamberts – A measurement of luminance. It is equal to $\frac{1}{1000\pi}$ $\frac{candles}{cm^2}$. (see candle in glossary)

minute of arc – One-sixtieth of a degree, which, in turn, is one-three hundred and sixtieth of a circle.

miotics – Drugs which cause contraction of the pupil.

mydriatics – Drugs which cause dilitation of the pupil.

optical aberrations – Failure of rays from a point source of light to form a perfect image on the retina after traversing the optical system of the eye.

optic atrophy – Degeneration of the nerve fibers of the optic nerve, usually most evident at the optic disc.

phorias – The relative directions assumed by the eyes during binocular fixation of a given object in the absence of an adequate fusion stimulus.

photopic vision – The luminance range, approximately 10^0 to 10^5 milli-lamberts, which involves only cone function.

psychotropics – Drugs which affect the psyche, used in the treatment of mental illnesses.

retinitis pigmentosa – Progressive atrophy of the retinal neuroepithelium with pigmentary infiltration of the inner layers.

retinopathy – Noninflammatory degenerative disease of the retina.

second of arc – One-sixtieth of a minute of arc.

scotopic vision – The luminance range, approximately 10^{-6} to 10^{-3} milli-lamberts, which involves only rod function.

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